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A key review on performance improvement aspects of geothermal district heating systems and applications

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Abstract

This paper deals with a comprehensive analysis and discussion of geothermal district heating systems and applications. In this regard, case studies are presented to study the thermodynamic aspects in terms of energy and exergy and performance improvement opportunities of three geothermal district heating systems, namely (i) Balcova geothermal district heating system (BGDHS), (ii) Salihli geothermal district heating system (SGDHS), and (iii) Gonen geothermal district heating system (GGDHS) installed in Turkey. Energy and exergy modeling of geothermal district heating systems for system analysis and performance evaluation are given, while their performances are evaluated using energy and exergy analysis method. Energy and exergy specifications are presented in tables. In the analysis, the actual system operational data are utilized.

Abbreviation: BGDHS, Balcova geothermal district heating system; ECC, energy consumption circuit; EDC, energy distribution circuit; EPC, energy production circuit; GDHS, geothermal district heating system; GGDHS, Gonen geothermal district heating system; IBGF, Izmir Balcova geothermal field; IBGDHS, Izmir Balcova geothermal district heating system; INGDHS, Izmir Narlidere geothermal district heating system; SGDHS, Salihli geothermal district heating system; W, water; TW, thermal water; TWR, thermal water re-injection

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In comparison of the local three district heating systems with each other, it is found that the SGDHS has highest energy efficiency, while the GGDHS has highest exergy efficiency.

Keywords: District heating; Geothermal energy; Energy; Exergy; Efficiency; Renewable energy; Thermodynamics

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1. Introduction

The non-electric applications of geothermal energy, with the exception of balneology, date back to the 19th century and have been given a new impetus by the recent oil crisis. Geothermal energy is used in agriculture, aquaculture, district heating, and cooling and various industrial applications. The environmental impact from geothermal energy is lower than that caused by conventional energy sources. Reinjection of used fluids back into the reservoir may, however, solve any pollution problems [1]. It appears likely that over the next 5–10 years, the growth rate of geothermal energy use for power generation will significantly increase [2].

Space heating with geothermal energy is one of the most common and widespread direct uses of geothermal resources. Space heating is also one of the oldest direct uses of geothermal energy. District heating, and in some cases district cooling, networks are designed to provide space heating and/or cooling to multiple consumers from a single well or from multiple wells or fields. The development of geothermal district heating, led by the Icelanders, has been one of the fastest growing segments of the geothermal space heating industry and now accounts for over 75% of all space heating provided from geothermal resources world wide [3]. The main uses of geothermal energy cover a wide range of applications, such as space heating and domestic hot water supply, aquaculture, greenhouse heating, swimming pool and balneology, industrial processes, heat pumps,

Nomenclature

$\dot{E}$	energy rate (kW)
$\dot{E}x$	exergy rate (kW)
$\dot{F}$	exergy rate of the fuel (kW)
f	exergetic factor (%)
h	specific enthalpy (kJ/kg)
$\dot{I}$	irreversibility (exergy destruction) rate (kW)
$\dot{m}$	mass flow rate (kg/s)
n	number of wellhead (–)
P	pressure (kPa)
$\dot{P}$	exergy rate of the product (kW)
R^2	correlation coefficient (–)
s	specific entropy (kJ/kg K)
$\dot{S}$	entropy rate (kW/K)
T	temperature (°C or K)
$\dot{W}$	work rate (or power) (kW)

Greek letters

η	energy (first law) efficiency (%)
ε	exergy (second law) efficiency (%)
ψ	specific flow exergy (kJ/kg)
δ	fuel depletion rate (%)
ξ	productivity lack (%)
χ	relative irreversibility (%)

Subscripts

0	reference (dead) state
a	ambient
$c1$, $c3$, $c5$	energy efficiency correlations
$c2$, $c4$, $c6$	exergy efficiency correlations
d	natural direct discharge
dest	destroyed
gen	generation
HE	heat exchanger
i	successive number of elements
in	inlet
out	outlet
r	reinjected thermal water
tot	total
w	well-head

and electricity generation. Based upon the current status, the majority of geothermal applications in Turkey have been realized in district heating systems [4].

Geothermal energy utilization is divided into two categories, i.e., electric energy production and direct uses for space heating and cooling, industrial processes, and greenhouse heating. Practical uses of geothermal energy for bathing, washing and cooking date back to prehistory. The earliest residential district heating in the world by geothermal water was in Chaude Aigues in France in the 14th century. The first municipal district heating system using geothermal water was set up in Reykjavik. Iceland in 1930. Recently, geothermal district heating has been successfully implemented in many countries, e.g. USA, France, Romania, Canada, Italy, Iceland and more recently Japan, New Zealand, China and Turkey [1–15]. Energy use growth in space heating since 2000 is 23.2% or 4.3% annually down from the 1995–2000 period in percentages, but increasing more in absolute numbers. The installed capacity is 4158 MW and the annual energy use is 52,868 TJ/yr. As stated earlier, about 77% of the annual energy use and 81% of the installed capacity is due to district heating. Iceland, Turkey, China and France are the leaders, mainly in district heating, whereas, Australia, Russia, USA and Japan dominate the individual home-heating systems use [15].

The total installed capacity, reported at the end of 2004, for the world's geothermal direct utilization is 27,825 MW, almost a two-fold increase over the 2000 data, growing at a compound rate of 12.9% annually. The total annual energy use is 261,418 TJ (72,622 GWh), almost a 40% increase over 2000, growing at a compound rate of 6.5% annually. Compared to 10 years ago the capacity increased 12.4%/yr and the use 8.8%/yr [15]. The countries with the largest installed capacity and annual energy use were the USA, Sweden, China, Iceland, and Turkey, accounting for about 66% of the installed capacity and 60% of the annual energy use [15].

Turkey's share in worldwide geothermal energy use is about 12.0%, and geothermal resources prior to 1960 were only used spontaneously in bathing and medical treatment. Recently, the General Directorate of Mineral Research and Exploitation in Turkey has carried out some considerable geothermal energy research and explorations. Although some inventorial works and chemical analyses of the hot springs and mineral waters were first initiated in 1962, geothermal district heating development essentially started in 1990 with the heating of 600 residences in Gonen, Balikesir. Geothermal direct use applications increased as steeply as 18.5% from 1990 to 1995 and this has brought Turkey to amongst the leading countries in geothermal development [3,14].

As far as geothermal systems are concerned, these studies can be classified into five groups as follows: (i) exergy analysis of geothermal power plants [16–25], (ii) evaluation of geothermal fields using exergy analysis [26,27], (iii) classification of geothermal resources by exergy [28], (iv) energy and exergy analysis geothermal district heating systems (GDHSs) [5–12], and (vi) exergoeconomic analysis of GDHSs [8–10,13].

The authors have conducted various studies on energy and exergy analysis of GDHSs [5–13]. The analysis in these studies was based on the actual outside air temperatures. A model to evaluate the contribution of geothermal energy sources for improving the heating performance of district heating systems was also proposed. As three case studies, the model was applied to the (i) Balcova geothermal district heating system (BGDHS) in Izmir, (ii) Salihli geothermal district heating system (SGDHS) in Manisa, and (iii) Gonen geothermal district heating system (GGDHS) in Balikesir, Turkey. In the present study, the performances of three GDHSs installed in Turkey are investigated in terms of energetic and exergetic aspects.

2. Geothermal district heating systems

The delivery of thermal energy from a central source is not a new idea. During Roman times, warm water was circulated through open trenches to provide heating for buildings and baths in Pompeii. In the ruins are the remains of the old heating plants, for example, the one used in conjunction with the so called Thermer (bath). In many places it is still possible to see how the heated water was circulated from home to home through a network of trenches that went through the cellars of buildings. Hundreds of years later, but several hundred years before our time, in Chaudes Aigues Cantal in France, geothermal water was distributed as early as the 14th Century through wooden pipes. That system is still used today. The French were already at that time utilizing a large main with laterals to provide heat to individual houses [3,29].

The in 2005 application of geothermal energy for direct utilization has been reviewed by Lund et al. [15]. According to their study, the 71 countries reporting direct utilization of geothermal energy is a significant increase from the 58 reported in 2000 and the 28 reported in 1995. The thermal energy used is 261,418 TJ/yr (72,622 GWh/yr), almost a 40% increase over 2000, growing at a compound rate of 6.5% annually. The distribution of thermal energy used by category is approximately 33% for geothermal heat pumps, 29% for bathing and swimming (including balneology), 20% for space heating (of which 77% is for district heating), 7.5% for greenhouse and open ground heating, 4% for industrial process heat, 4% for aquaculture pond, and raceway heating, $<1\%$ for agricultural drying, $<1\%$ for snow melting and cooling, and $<0.5\%$ for other uses.

Fig. 1 shows a schematic diagram of the simplified GDHS where user system is heated by geothermal energy. A GDHS consists mainly of three circuits, namely (a) energy production circuit (EPC; geothermal well loop), (b) energy distribution circuit (EDC; district heating distribution network), and (c) energy consumption circuit (ECC).

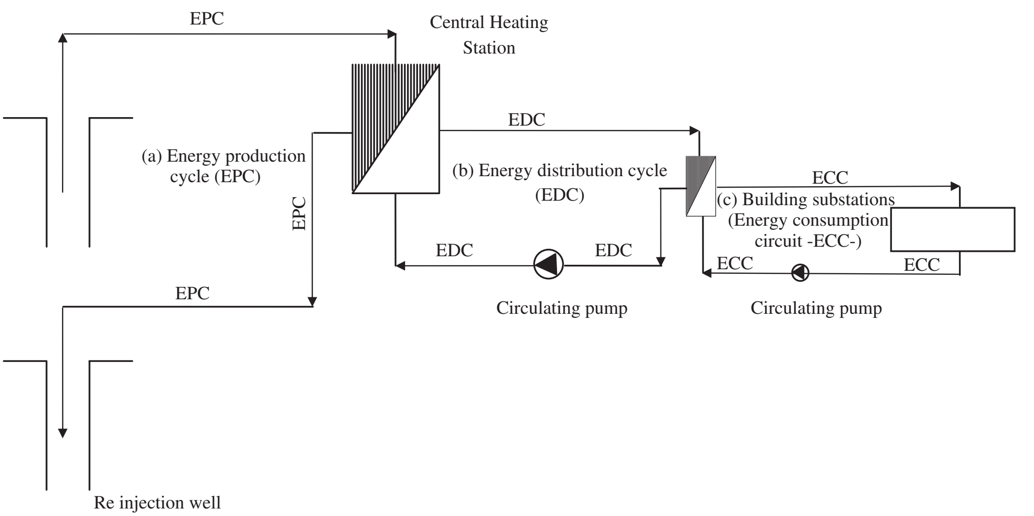

Fig. 1. Simplified flowchart of the geothermal district heating system.

3. Energy and exergy analysis

3.1. Energy analysis

The balance equations are written for mass and energy flows in the BGDHS, SGDHS, and GGDHS and their components as they are considered steady-state steady-flow control volume systems and the appropriate energy equations are derived for these systems and their components. Neglected are the pressure drops due to the liquid flow friction, and thermal water of intermingling molecules of different species through molecular diffusion in this study. The reference state for the BGDHS, SGDHS, and GGDHS were considered to be 4 °C, and the atmospheric pressure was taken as 101.32 kPa, for the all systems. In the present case studies performed on the BGDHS SGDHS, and GGDHS, the hourly recorded experimental thermal data of various parameters (e.g., temperatures, pressures and volumetric flow rates) were taken directly from the system technical staff, who conducted the measurements of pressures and temperatures of fluids (including water) through the Bourdon-tube pressure gauges and fluid-expansion thermometers, respectively.

For a general steady state, steady-flow process, the two balance equations, namely mass, energy balance equations, are employed to find the heat input, and the energy efficiencies.

In general, the mass balance equation can be expressed in the rate form as

$$\sum \dot{m}_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}}, \tag{1}$$

where $\dot{m}$ is the mass flow rate, and the subscript in stands for inlet and out for outlet.

For the all GDHSs studied, the mass balance equations are written by

$$\sum_{i=1}^{n} \dot{m}_{\mathrm{w,tot}} - \dot{m}_{\mathrm{r}} - \dot{m}_{\mathrm{d}} = 0 \text{ for the BGDHS and GGDHS} \tag{2a}$$

and

$$\sum_{i=1}^{n} \dot{m}_{\mathrm{w,tot}} - \dot{m}_{\mathrm{d}} = 0 \text{ for the SGDHS,} \tag{2b}$$

where $\dot{m}_{\mathrm{w,tot}}$ is the total mass flow rate at wellhead, $\dot{m}_{\mathrm{r}}$ is the flow rate of the reinjected thermal water, and $\dot{m}_{\mathrm{d}}$ is the mass flow rate of the natural direct discharge.

The general energy balance can be expressed below as the total energy input equal to total energy output ($\dot{E}_{\mathrm{in}} = \dot{E}_{\mathrm{out}}$), with all energy terms as follows:

$$\sum \dot{m}_{\mathrm{in}} h_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}} h_{\mathrm{out}}. \tag{3}$$

The geothermal brine energy inputs from the production field of the all systems investigated are calculated from the following equation:

$$\dot{E}_{\mathrm{brine}} = \dot{m}_{\mathrm{w}} \left(h_{\mathrm{brine}} - h_0 \right). \tag{4}$$

Basically, the energy efficiency of the system can be defined as the ratio of total energy output to total energy input

$$\eta = \frac{\dot{E}_{\mathrm{output}}}{\dot{E}_{\mathrm{input}}}, \tag{5a}$$

where in most cases "output" refers to "useful" one.

Based upon Eq. (5a), the energy efficiencies of the all systems are calculated from

$$\eta_{\text{system}} = \frac{\dot{E}_{\text{useful,HE}}}{\dot{E}_{\text{brine}}}. \tag{5b}$$

3.2. Exergy analyses

The balance equations are written for exergy flows in the BGDHS, SGDHS, and GGDHS and their components as they are considered steady-state steady-flow control volume systems and the appropriate exergy equations are derived for these systems and their components.

The geothermal brine exergy inputs from the production field of the three GDHSs investigated are calculated from the following equations:

$$\dot{E}x_{\text{brine}} = \dot{m}_{\text{w}}[(h_{\text{brine}} - h_0) - T_0(s_{\text{brine}} - s_0)]. \tag{6}$$

It is usually more convenient to find entropy generation $\dot{S}_{\text{gen}}$ first, and then to evaluate the exergy destroyed or the irreversibility $\dot{E}x_{\text{dest}}$ directly from the following equation.

$$\dot{E}x_{\text{dest}} = T_0\dot{S}_{\text{gen}}. \tag{7}$$

The exergy destructions in the heat exchanger, pump and the system itself are calculated using:

$$\dot{E}x_{\text{dest,HE}} = \dot{E}x_{\text{in}} - \dot{E}x_{\text{out}} = \dot{E}x_{\text{dest}}, \tag{8}$$

$$\dot{E}x_{\text{dest,pump}} = \dot{W}_{\text{pump}} - \left(\dot{E}x_{\text{out}} - \dot{E}x_{\text{in}}\right) \tag{9}$$

and

$$\dot{E}x_{\text{dest,system}} = \sum \dot{E}x_{\text{dest,HE}} + \sum \dot{E}x_{\text{dest,pump}}. \tag{10}$$

The exergy efficiency of a heat exchanger is determined by the increase in the exergy of the cold stream divided by the decrease in the exergy of the hot stream on a rate basis as follows:

$$\varepsilon_{\text{HE}} = \frac{\dot{m}_{\text{cold}}(\psi_{\text{cold,out}} - \psi_{\text{cold,in}})}{\dot{m}_{\text{hot}}(\psi_{\text{hot,in}} - \psi_{\text{hot,out}})}. \tag{11}$$

Numerous ways of formulating exergetic (or exergy or second-law) efficiency (effectiveness or rational efficiency) for various energy systems are given in detail elsewhere [30]. In a similar way, we define exergy efficiency as the ratio of total exergy output to total exergy input:

$$\varepsilon = \frac{\dot{E}x_{\text{output}}}{\dot{E}x_{\text{input}}}, \tag{12a}$$

where "output" refers to "net output" or "product" or "desired value", and "input" refers to "given" or "used".

The exergy efficiencies of the BGDHS, SGDHS, and GGDHS are calculated from the following equations as follows:

$$\varepsilon_{\text{system}} = \frac{\dot{E}x_{\text{useful,HE}}}{\dot{E}x_{\text{brine}}} = 1 - \frac{\dot{E}x_{\text{dest,system}} + \dot{E}x_{\text{reinjected}} + \dot{E}x_{\text{natural disch arged}}}{\dot{E}x_{\text{brine}}} \quad \text{for the BGDHS and GGDHS,} \tag{12b}$$

$$\varepsilon_{\text{system}} = \frac{\dot{E}x_{\text{useful,HE}}}{\dot{E}x_{\text{brine}}} = 1 - \frac{\dot{E}x_{\text{dest,system}} + \dot{E}x_{\text{natural discharged}}}{\dot{E}x_{\text{brine}}} \quad \text{for the SGDHS.} \tag{12c}$$

3.3. Some thermodynamics performance parameters

Thermodynamics analysis of thermal and geothermal energy systems may also be performed using the following parameters [5–7,9,31].

- Fuel depletion ratio:

$$\delta_i = \frac{\dot{I}_i}{\dot{F}_{\text{tot}}}. \tag{13}$$

- Relative irreversibility:

$$\chi_i = \frac{\dot{I}_i}{\dot{I}_{\text{tot}}}. \tag{14}$$

- Productivity lack:

$$\xi_i = \frac{\dot{I}_i}{\dot{P}_{\text{tot}}}. \tag{15}$$

- Exergetic factor:

$$f_i = \frac{\dot{F}_i}{\dot{F}_{\text{tot}}}. \tag{16}$$

4. Case studies

4.1. Balcova geothermal district heating system (BGDHS)

The Izmir–Balcova geothermal field covers a total area of about 3.5 km^2 with an average thickness of the aquifer horizon of 150 m. Assume that no feeding occurs, and 25% of the fluid contained in the reservoir is utilized. The field has a maximum yield of 0.225 m^3/s at a reservoir temperature of 118 °C. The present district heating system consists of the

Izmir–Balcova geothermal district heating system (IBGDHS) and the Izmir–Narlidere geothermal district heating system (INGDHS). The design heating capacity of the IBGDHS is equivalent to 7500 residences (one residence equivalence means a peak heating load of about 6.38 kW for a dwelling of 100 m^2). The INGDHS was designed for 1500 residence equivalence, but has a sufficient infrastructure to allow a capacity growth to 5000 residence equivalence. The outdoor and indoor design temperatures for the two systems are 0 and 22 °C, respectively [10]. Both IBGDHS and INGDHS are investigated here under the BGDHS (for more details, see Refs. [5,8–11]). The BGDHS is presently run by an institution under the governorship of Izmir and is utilized only for district heating purposes.

Fig. 2 shows a schematic diagram of the BGDHS where hotels and official buildings heated by geothermal energy are also included. The BGDHS consists mainly of three circuits, e.g. (a) EPC (geothermal well loop—BDs, Bs, and BD8 reinjection wells lines), (b) EDC (district heating distribution network—from main collector to heat exchangers (I–XIII) lines), and (c) ECC partly described (building substations—from heat exchangers (I–XIII) to users' heat exchangers). Here, BDs stand for deep wells and Bs stand for shallow wells.

As of the end of 2001, there were 14 wells ranging in depth from 48 to 1100 m in the IBGF, while nine wells were working at the date studied. Of these, eight wells (designated as BD2, BD3, BD4, BD5, BD7, B1, B4, and B5) and one well (BD8) are production and reinjection wells, respectively. The well head temperatures of the production wells vary from 95 to 140 °C, while the volumetric flow rates of the wells range from 0.0083 to 0.0417 m^3/s, respectively. The thermal water is then sent to two primary plate type heat exchangers and is cooled to about 60–62 °C, as its heat is transferred to secondary fluid. The primary thermal water is reinjected into the well BD8 after extracting enthalpy, internal energy, entropy, etc., while the secondary fluid is utilized to heat the buildings through the substation heat exchangers. The average conversion temperatures obtained during the operation of the BGDHS are 80/57 °C for the district heating distribution network and 60/45 °C for the building circuit. Using the control valves for flow rate and temperature at the building substations, the required amount of water is sent to each housing unit to achieve the heat balance of the system [5,6,9,11].

4.2. *Salihli geothermal district heating system (SGDHS)*

The Salihli geothermal field is about 7 km distance from the town of Salihli (about 55 km far from the city of Manisa, located in the western part of Turkey) and is abounded with considerably rich geothermal resources. It has a maximal yield of 0.087 m^3/s at an average reservoir temperature of 95 °C, with a minimal capacity of 838 MW. The SGDHS was initially designed for a capacity to cover 20,000 residences equivalence. Of these, 2400 residences equivalence are heated by geothermal energy as of February 2004. The outdoor and indoor design temperatures for the system are 4 and 22 °C, respectively.

Fig. 3 illustrates a schematic of the SGDHS, where two hospitals and official buildings heated by geothermal energy were also included. The SGDHS consists mainly of three cycles, such as: (a) energy production cycle (geothermal well loop and geothermal heating center loop), (b) energy distribution cycle (district heating distribution network), and (c) energy consumption cycle (building substations).

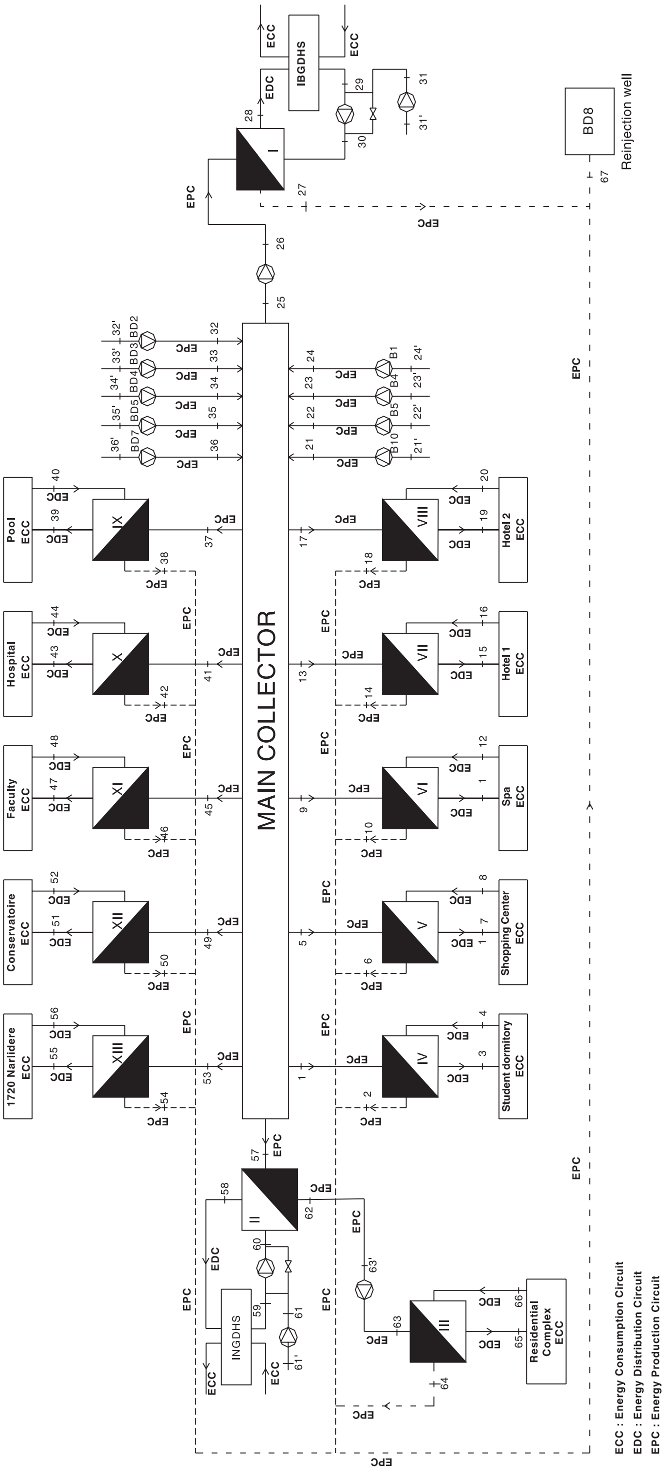

Fig. 2. Schematic layout of the BGDHS [5,6,9,11].

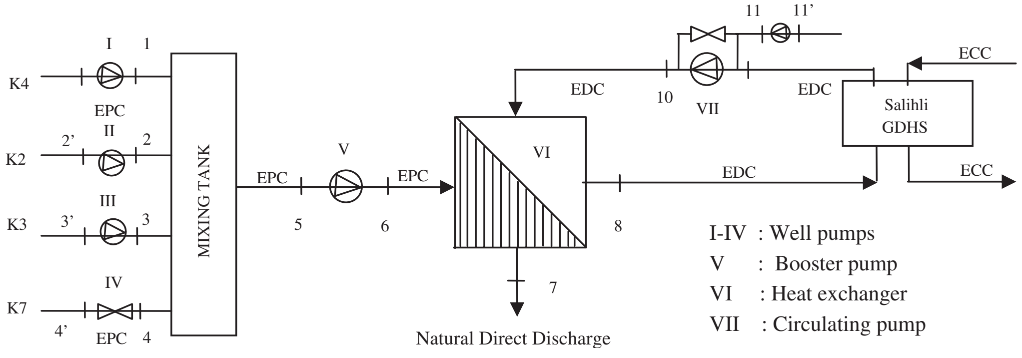

Fig. 3. Schematic diagram of the SGDHS [7,9].

At the beginning of this year, there were seven wells ranging in depth from 70 to 262 m in the SGDHS. Of these, five wells were in operation at the date studied and two wells (K5 and K6) were out of operation. Four wells (designated as K2, K3, K4 and K7) and one well (K1) are production and balneology wells, respectively. The well head temperatures of the production wells vary from 56 to 115 °C, while the volumetric flow rates of the wells range from 0.002 to 0.02 m^3/s. Geothermal fluid is sent to the primary plate type heat exchanger (between the geothermal fluid and the district heating water) and is cooled to about 44 °C, as its heat is transferred to the district heating water.

The geothermal fluid (7) is discharged via natural direct discharge, no recharge to Salihli geothermal field, but reinjection studies are expected to be completed in the near future. The temperatures obtained during the operation of the SGDHS are, on average, 96/44 °C for the district heating distribution network and 62/43 °C for the building circuit. By using the control valves for flow rate and temperature at the building main station, the needed amount of water is sent to each housing unit and the heat balance of the system is achieved. Geothermal fluid, collected from the four production wells at an average well heat temperature of about 96 °C, is pumped to the inlet of the heat exchanger mixing tank later a main collector (from four production wells) with a total mass flow rate of about 44.39 kg/s. Geothermal fluid of intermingling molecules of different species through molecular diffusion was neglected in this study.

The mixing of water streams of different temperatures is practically the key problem from the exergy viewpoint. The exergy loss due to the mixing varies dependently on the rates and temperatures of the streams. As a result, not only irreversibility of the mixing tank was assumed equal to zero but also heat losses from the tank and main collector pipe lines (5–6) through the mixing process were neglected [7,9].

4.3. Gonen geothermal district heating system (GGDHS)

The Balikesir–Gonen geothermal field covers a total area of about 1.5 km^2 with an average thickness of the aquifer horizon of 300 m. The Gonen geothermal area is about 114 km from the city of Balikesir, located in the western part of Turkey, and abounds with considerably rich geothermal resources. It has a maximum yield of 0.150 m^3/s at an average reservoir temperature of about 70 °C. The GGDHS was initially designed for a capacity to cover 3600 residences equivalence. Fig. 4 illustrates a schematic diagram of the GGDHS,

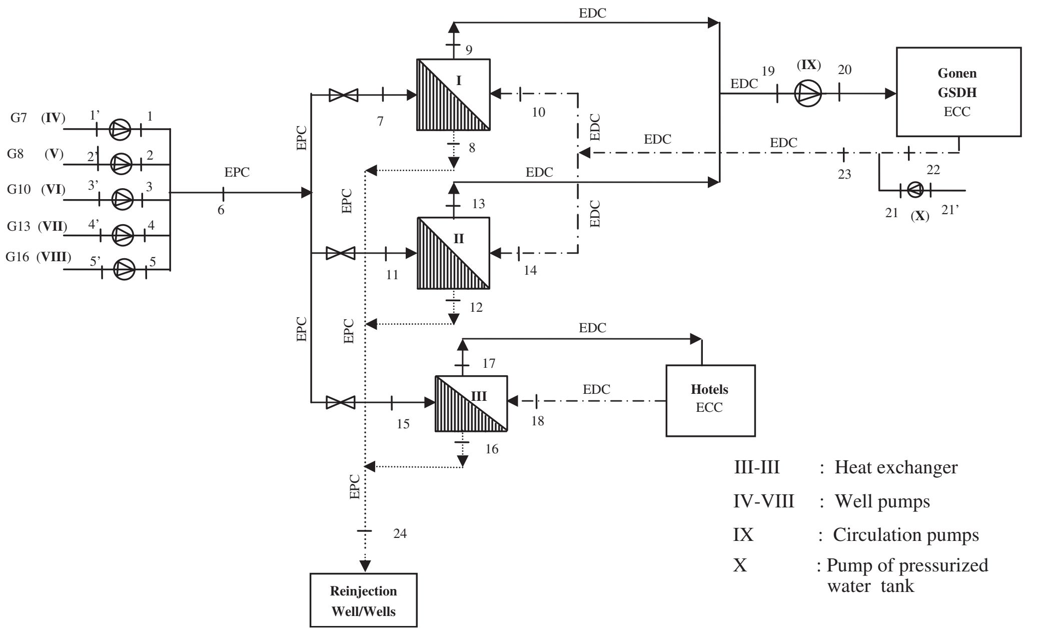

Fig. 4. Schematic diagram of the GGDHS [12].

including hotels and dwellings heated by geothermal energy. The GGDHS has balneology and small industrial heating applications. It consists mainly of three circuits, e.g., (a) EPC or geothermal well loop, (b) EDC or district heating distribution network, and (c) ECC. The temperatures of the production wells (Gs) essentially vary from 58 to 92 °C, while the mass flow rates of the wells range from 6 to 35 kg/s, respectively. The thermal water is then sent to two primary plate type heat exchangers and is cooled to about 40–42 °C, as its enthalpy is transferred to the secondary fluid. At the beginning of this year, there were 10 production wells. Of these, five wells (designated as G7, G8, G10, G13, and G16) were in operation at the date studied. Four wells (designated as G3, G5, G14, and G15) in the system are reinjection wells. The primary thermal water is reinjected into the wells after extracting its enthalpy, while the secondary fluid (i.e., clean hot water) is utilized to heat the buildings through the substation heat exchangers. The average inlet outlet (conversion) temperatures of thermal water obtained during the operation of the GGDHS are 70/40 °C for the district heating distribution network and 52/42 °C for the building circuit. Using the control valves for flow rate and temperature at the building substations, the required amount of water is sent to each housing unit to achieve the heat balance of the system. The thermal water, collected from production wells at an average well head temperature of 70–72 °C, is sent to a main heat center from production wells [12].

5. Results and discussion

The temperature, pressure, and mass flow rate data for both thermal water and water are given in accordance with their state numbers specified in Figs. 2–4. The energy and exergy

Table 1
Exergy rates and other properties at various system locations for one representative unit

State no.	Fluid type	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Energy rate $\dot{E}$ (kW)	Specific exergy ψ (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
0	W	4	101.325	17.69	6.05E−02	—	—	—	—
1	TW	105	222.11	439.95	1.3623	11.2	4729.31	61.454	688.29
2	TWR	55	117.05	230.02	0.7671	11.2	2378.10	16.484	184.62
3	W	80	148.67	334.71	1.0744	18.71	5931.44	36.006	673.67
4	W	50	113.65	209.13	0.703	18.71	3581.84	13.359	249.96
5	TW	105	222.11	439.95	1.3623	5.82	2457.55	61.454	357.67
6	TWR	80	148.67	334.71	1.0744	5.82	1845.06	36.006	209.55
7	W	55	117.05	230.02	0.7671	9.72	2063.85	16.484	160.23
8	W	50	113.65	209.13	0.703	9.72	1860.80	13.359	129.85
9	TW	90	171.42	376.7	1.1917	4.88	1751.97	45.486	221.97
10	TWR	57	118.62	238.38	0.7952	4.88	1076.97	17.056	83.23
11	W	85	159.11	355.71	1.1334	5.37	1815.17	40.654	218.31
12	W	55	117.05	230.02	0.7671	5.37	1140.21	16.484	88.52
13	TW	90	171.42	376.7	1.1917	5.42	1945.83	45.486	246.54
14	TWR	57	118.62	238.38	0.7952	5.42	1196.14	17.056	92.44
15	W	85	159.11	355.71	1.1334	5.97	2017.98	40.654	242.71
16	W	55	117.05	230.02	0.7671	5.97	1267.61	16.484	98.41
17	TW	75	139.86	313.74	1.0146	25.47	7540.39	31.610	805.10
18	TWR	60	121.23	250.93	0.8303	25.47	5940.62	19.878	506.30
19	W	70	132.47	292.78	0.954	19.12	5259.72	27.445	524.75
20	W	50	113.65	209.13	0.703	19.12	3660.33	13.359	255.43
21	TW	102.3	354.63	428.73	1.3321	34.55	14,201.43	58.604	2024.78
21′	TW	102	210.1	427.29	1.3287	34.55	14,151.68	58.107	2007.59
22	TW	106.7	354.63	447.3	1.3813	25.42	10,920.69	63.539	1615.15
22′	TW	106.4	228.1	445.87	1.3779	25.42	10,884.34	63.051	1602.76
23	TW	101.1	354.63	423.67	1.3186	8.51	3454.89	57.286	487.50
23′	TW	100.8	205.57	422.22	1.3152	8.51	3442.55	56.778	483.18
24	TW	101.4	486.36	425.04	1.3219	25.27	10,293.73	57.741	1459.12
24′	TW	101.1	206.68	423.49	1.3186	25.27	10,254.57	57.106	1443.07
25	TW	116.7	324.24	489.59	1.4913	78.49	37,039.43	75.342	5913.60
26	TW	117	557.28	491.02	1.4945	78.49	37,151.67	75.885	5956.23
27	TW	62	506.62	259.68	0.8553	78.49	18,993.80	21.700	1703.20
28	W	89.4	689.01	374.67	1.1847	150.78	53,825.44	45.396	6844.86
29	W	60.7	420.49	254.18	0.8391	144.85	34,255.58	20.689	2996.86
30	W	61	790.33	255.74	0.8428	150.78	35,893.18	21.224	3200.14
31	W	13.3	350	56.66	0.1995	5.93	231.09	0.435	2.58
31′	W	13	200	55.27	0.1951	5.93	222.85	0.264	1.57
32	TW	133.9	404.53	562.72	1.6748	19.13	10,426.42	97.615	1867.38
32′	TW	133.6	401.87	561.44	1.6717	19.13	10,401.94	97.194	1859.33
33	TW	130.1	455.96	546.62	1.6349	19.98	10,568.02	92.573	1849.62
33′	TW	129.8	369.85	545.21	1.6317	19.98	10,539.85	92.050	1839.16
34	TW	136.5	506.63	573.96	1.702	41.82	23,263.21	101.317	4237.06
34′	TW	136.2	425.5	572.56	1.6989	41.82	23,204.66	100.776	4214.44
35	TW	120.4	557.28	505.45	1.5313	21.73	10,599.02	80.116	1740.92
35′	TW	120.1	300.51	503.92	1.5281	21.73	10,565.78	79.473	1726.95
36	TW	117.5	455.96	493.08	1.5	15.75	7487.39	76.421	1203.63
36′	TW	117.2	282.89	491.6	1.4967	15.75	7464.08	75.856	1194.72
37	TW	90	171.42	376.73	1.1917	3.66	1314.09	45.516	166.59
38	TWR	57	118.62	238.38	0.7925	3.66	807.73	17.805	65.16

Table 1 (*continued*)

State no.	Fluid type	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Energy rate $\dot{E}$ (kW)	Specific exergy ψ (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
39	W	85	159.11	355.71	1.1334	4.02	1358.84	40.654	163.43
40	W	55	117.05	230.02	0.7671	4.02	853.57	16.484	66.27
41	TW	105	222.11	439.95	1.3623	51.95	21,936.41	61.454	3192.56
42	TWR	65	126.32	271.85	0.8925	51.95	13,203.61	23.560	1223.92
43	W	80	148.67	334.72	1.0744	104.72	33,199.38	36.016	3771.59
44	W	60	121.24	250.93	0.8303	104.72	24,424.89	19.878	2081.65
45	TW	107.3	486.36	449.94	1.388	1.32	570.57	64.322	84.90
46	TWR	78.7	303.97	327.76	1.0541	1.32	409.29	34.682	45.78
47	W	80	162.12	334.78	1.0744	2.09	662.72	36.076	75.40
48	W	61.7	212.78	258.18	0.8515	2.09	502.62	21.253	44.42
49	TW	110	486.36	461.35	1.4179	0.2	88.73	67.445	13.49
50	TWR	50	113.65	209.13	0.703	0.2	38.29	13.359	2.67
51	W	65	263.44	272.02	0.8925	0.42	106.82	23.730	9.97
52	W	36.6	273.57	153.52	0.5264	0.42	57.05	6.694	2.81
53	TW	111.6	486.36	460.11	1.4355	9.4	4158.75	61.327	576.47
54	TWR	80	148.67	334.71	1.0744	9.4	2979.99	36.006	338.46
55	W	81	303.97	339.09	1.0863	12.83	4123.56	37.088	475.84
56	W	57.7	364.77	241.59	0.8014	12.83	2872.64	18.548	237.97
57	TW	108	425.56	452.85	1.3957	16.3	7093.11	65.098	1061.09
58	W	90	496.49	377.04	1.1917	24.21	8699.86	45.826	1109.45
59	W	56	385	234.51	0.7798	24.21	5249.21	17.454	422.57
60	W	56.3	618.08	235.96	0.7836	24.21	5284.32	17.851	432.18
61	—	—	—	—	—	—	—	—	—
61′	—	—	—	—	—	—	—	—	—
62	TWR	58	398.2	242.87	0.8051	16.3	3670.43	18.802	306.48
63	TW	58	398.2	242.87	0.8051	16.3	3670.43	18.802	306.48
63′	TW	57.7	119.2	241.31	0.8013	16.3	3645.01	18.296	298.22
64	TWR	40	108.69	167.37	0.572	16.3	2439.78	7.906	128.87
65	W	47	111.93	196.6	0.6642	29.84	5338.67	11.583	345.63
66	W	37	107.6	154.85	0.5319	29.84	4092.85	6.500	193.96
67	TWR	64	364.77	267.93	0.8801	114.76	28,717.54	23.076	2648.23

State numbers refer to Fig. 1 for the BGDHS.

Note: The phase of the reference state is liquid: (0) reference state; W, water; TW thermal water; TWR, thermal water re-injection.

rates are calculated for each state and are listed in Tables 1–3. Note that state 0 indicates the reference (dead) state for the thermal water. For thermal water, the thermodynamic properties of water are used. By doing so, any possible effects of salts and noncondensable gases that might be present in the geothermal brine are neglected [3–5,11–13]. The thermodynamic properties of water are obtained from the general thermodynamic tables and software. The number of the wells in operation in the Balcova, Salihli, and Gonen geothermal fields may vary depending on the heating days and operating strategy.

5.1. *The performance evaluation results of the BGDHS*

Using Eq. (2a), the total geothermal reinjection fluid (the thermal water reinjected into the well BD8) mass flow rate is 114.76 kg/s at an average temperature of 64 °C and the

Table 2
Exergy rates and other properties at various system locations for one representative unit

State no.	Fluid type	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Energy rate $\dot{E}$ (kW)	Specific exergy ψ (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
0	W	4	101.325	17.69	6.05E−02	—	—	—	—
1	TW	56	117.83	234.2	0.7798	6.3	1364.01	17.156	108.08
1′	TW	55.3	117.29	231.28	0.7709	6.3	1345.62	16.703	105.23
2	TW	98	195.62	410.42	1.2835	9.18	3605.26	53.776	493.66
2′	TW	97.3	193.26	407.46	1.2755	9.18	3578.09	53.033	486.84
3	TW	98	195.62	410.42	1.2835	19.18	7532.56	53.776	1031.42
3′	TW	97.3	193.26	407.46	1.2755	19.18	7475.79	53.033	1017.17
4	TW	115	270.39	482.27	1.4728	9.73	4520.36	73.161	711.86
4′	TW	114.3	266.56	479.3	1.4651	9.73	4491.47	72.325	703.72
5	TW	95	185.83	397.78	1.2493	44.39	16,872.20	50.614	2246.76
6	TW	95.7	435.7	400.98	1.2573	44.39	17,014.24	51.597	2290.39
7	TWR	44.8	395.17	187.8	0.6354	44.39	7551.18	10.776	478.37
8	W	62	445.83	259.63	0.8553	120.82	29,231.19	21.661	2617.10
9	W	42.8	109.86	179.07	0.6091	116.49	18,799.16	9.336	1087.49
10	W	43.5	354.64	182.34	0.6183	120.82	19,893.01	10.056	1214.93

State numbers refer to Fig. 2 for the SGDHS.
Note: The phase of the reference state is liquid: (0) reference state; W, water; TW, thermal water; TWR, thermal water re-injection.

production well total mass flow rate is 212.16 kg/s, and the natural direct discharge of the system is then calculated to be 97.4 kg/s. This clearly indicates that in the BGDHS, there is a significant amount of hot water lost through leaks in the hot water distribution network [11].

Using the values given in Eqs. (5b) and (12b), the energy and exergy efficiencies of the BGDHS are determined to be 39.6% and 45.7%, respectively. The energy and exergy specifications are illustrated in Tables 4 and 5. The thermal reinjection accounts for 28.37% of the total energy input, while the natural direct discharge (pipe line losses) of the system cover its 32%.

Table 5 shows that 54.3% of the total exergy entering the system is lost, while the remaining 45.7% is utilized. The highest exergy lost of 29.3% occurs from the natural direct discharge (pipe line losses) of the system due to a significant amount of water leaks and includes some part of the exergy destructions through the primary and secondary fluid networks, which were not determined in this study. The second largest exergy destruction occurs from the thermal reinjection with 16.06% (corresponding to about 2648.23 kW) of the total exergy input. This is followed by the total exergy destruction associated with the pumps and heat exchangers amounts to some 1480 kW, which accounts for 8.97% of the total exergy input to the system.

5.2. The performance evaluation results of the SGDHS

The total mass flow rate of the geothermal fluid at the inlet of the heat exchanger (so-called: the total mass flow rate of the production wells) was measured to be 44.39 kg/s at an

Table 3
Exergy rates and other properties at various system locations for one representative unit

State no.	Fluid type	Temperature T (°C)	Pressure P (kPa)	Specific enthalpy h (kJ/kg)	Specific entropy s (kJ/kg K)	Mass flow rate $\dot{m}$ (kg/s)	Energy rate $\dot{E}$ (kW)	Specific exergy ψ (kJ/kg)	Exergy rate $\dot{E}x$ (kW)
0	W	4	101.325	17.69	6.05E−02	—	—	—	—
1	TW	58	303.97	242.79	0.8051	30	6753.00	18.734	562.02
1′	TW	57.3	118.87	239.64	0.7963	30	6658.50	18.023	540.69
2	TW	60	293.84	251.14	0.8303	20	4669.00	20.100	402.00
2′	TW	59.3	120.59	248	0.8215	20	4606.20	19.399	387.98
3	TW	69	314.11	288.8	0.9417	20	5422.20	26.885	537.71
3′	TW	68.3	130.25	285.66	0.9332	20	5359.40	26.101	522.02
4	TW	72	263.44	301.33	0.9783	20	5672.80	29.272	585.43
4′	TW	71.3	134.26	298.23	0.9698	20	5610.80	28.528	570.55
5	TW	81	314.11	339.1	1.0862	20	6428.20	37.137	742.74
5′	TW	80.3	149.24	335.97	1.0779	20	6365.60	36.308	726.15
6	TW	68	303.97	284.61	0.9295	110	29,361.20	26.077	2868.43
7	TW	68	303.97	284.61	0.9295	61.1	16,308.81	26.077	1593.28
8	TW	40	202.65	167.62	0.572	61.1	9160.72	8.168	499.05
9	W	52	506.62	217.92	0.7288	170	34,039.10	15.011	2551.81
10	W	42	253.31	176	0.5985	170	26,912.70	9.203	1564.56
11	TW	68	303.97	284.61	0.9295	36.7	9795.96	26.077	957.01
12	TW	40	202.65	167.62	0.572	36.7	5502.43	8.168	299.76
13	W	52	506.62	217.92	0.7288	102	20,423.46	15.011	1531.09
14	W	42	202.65	175.95	0.5985	102	16,142.52	9.153	933.64
15	TW	68	303.97	284.61	0.9295	12.2	3256.42	26.077	318.14
16	TW	40	202.65	167.62	0.572	12.2	1829.15	8.168	99.65
17	W	52	506.62	217.92	0.7288	34	6807.82	15.011	510.36
18	W	42	253.31	176	0.5985	34	5382.54	9.203	312.91
19	W	51.3	506.62	215	0.7198	272	53,668.32	14.585	3967.12
20	W	52	557.28	217.96	0.7288	272	54,473.44	15.051	4093.78
21	W	8	506.62	34.75	0.121	2.3	39.24	0.292	0.67
21′	W	7.3	455.96	31.79	0.1104	2.3	32.43	0.270	0.62
22	W	42	253.31	176	0.5985	269.7	42,696.21	9.203	2482.13
23	W	42	253.31	176	0.5985	272	43,060.32	9.203	2503.30
24	TWR	39	202.65	163.46	0.572	110	16,034.70	4.008	440.86

State numbers refer to Fig. 3 for the GGDHS.
Note: The phase of the reference state is liquid: (0) reference state; W, water; TW, thermal water; TWR, thermal water re-injection.

average temperature of 91.8 °C. Using Eq. (2b), the total mass flow rate of the natural direct discharge fluid is found to be 44.39 kg/s in the SGDHS. In the SGDHS, if hot water losses measured in the district heating distribution network are above 0.0014 m^3/s, the water is added via a pump through pressurized water tanks to this network for covering these leaks. Note that in the analysis the hot water losses are neglected since the losses were under 0.0014 m^3/s on the date that the measurements were taken.

Using the values given in Eqs. (5b)–(12c), the energy and exergy efficiencies of the SGDHS are determined to be 55.6% and 59.8%, respectively. Energy and exergy specifications of the system are illustrated in Tables 5 and 6. The pipeline leak losses of the

Table 4
Energetic and exergetic data provided for one representative unit of the system (reference state temperature and the atmospheric pressure are 4 °C and 101.32 kPa, respectively) for BGDHS

Components	Exergy destruction rate (kW)	Utilized power (kW)	Heat transfer rate or installed power (kW)	$\dot{P}$ (kW)	$\dot{F}$ (kW)	Energy efficiency (%)	Exergy efficiency (%)
Heat exchanger							
I	608.32	18,157.09	50,364	3644.72	4253.04	—	86
II	77.34	3422.18	5800	677.28	754.61	—	90
III	25.93	1226.99	2310	151.68	177.61	—	85
IV	79.95	2350.32	3372	423.72	503.67	—	84
V	117.74	1221.33	4651	30.37	148.11	—	21
VI	8.95	675.08	2200	129.79	138.74	—	94
VII	9.80	749.78	1700	144.29	154.09	—	94
VIII	29.48	1600.02	3200	269.31	298.80	—	90
IX	4.26	506.31	1275	97.16	101.42	—	96
X	278.70	8729.68	15,700	1689.94	1968.64	—	86
XI	8.14	161.71	2326	30.98	39.12	—	79
XII	3.66	50.36	1117	7.15	10.82	—	66
XIII	0.15	1251.43	1316	237.87	238.02	—	99
Well pump							
B10	10.25	27.45	45	17.2	27.45	65–80	63
B5	25.85	38.25	75	12.4	38.25	65–80	32
B4	9.43	13.75	55	4.32	13.75	65–80	31
B1	15.29	31.35	55	16.06	31.35	65–80	51
BD2	6.95	15	75	8.05	15	65–80	54
BD3	28.05	38.5	110	10	38.5	65–80	27
BD4	30.18	52.8	110	22.62	52.8	65–80	43
BD5	16.83	30.8	55	13.97	30.8	65–80	45
BD7	23.54	32.45	55	8.91	32.45	65–80	27
Booster Pump: Balcova	25.37	68	200	42.63	68	65–80	63
Booster Pump: Caglayan	13.74	22	22	8.26	22	65–80	38
Circulation pump: Balcova	6.71	192	480	185.29	192	65–80	97
Circulation pump: Narlıdere	5.39	15	30	9.61	15	65–80	64
Pump of pressurized water tank: Balcova	9.99	11	11	1.01	11	65–80	0.9
Pump of pressurized water tank: Narlıdere	0	—	4	—	—	65–80	—
Heat exchangers (I–XIII)	1295.88	40,102.28	95,331	7534.26	8786.69	—	—
Pumps	227.58	588.35	1382	360.33	588.35	—	—
Overall system[a]	8950.91	40,690.63	96,713	7894.59	9375.04	39.6	45.7

[a]Based on the exergy (or energy) input to thermal water.

system account for 44.36% of the total energy input. An investigation of the exergy balance given in Tables 5 and 6 show that 40.2% (about 953.48 kW) of the exergy entering the system are lost, while the remaining 59.8% are utilized effectively. The highest exergy

Table 5
Energy and exergy specifications of the GDHSs studied

	Geothermal district heating systems		
	BGDHS	SGDHS	GGDHS
Energetic evaluation results			
Rate of total energy input (kW)	101,215.2	17,022.23	28,945.2
Rate of energy losses of pipe line (kW)	32,395.35	7551.18	41.60
Energy rate of thermal reinjection (kW)	28,717.54	—	16,034.70
Heat exchanger utilized power (kW)	40,102.31	9471.05	12,868.90
Energy efficiency (%)	39.6	55.6	44.5
Exergetic evaluation results			
Rate of total exergy input (kW)	16,485.17	2345.01	2829.91
Rate of exergy losses of pumps (kW)	227.58	65.26	386.78
Rate of exegy losses of heat exchanger (kW)	1252.42	409.85	187.83
Rate of exergy losses of pipe line (kW)	4822.67	478.37	32.30
Exergy rate of thermal reinjection (kW)	2648.23	—	440.86
Exergy rate of the product (kW)	7534.26	1402.17	1782.15
Exergy efficiency (%)	45.7	59.8	63

Table 6
Energetic and exergetic data provided for one representative unit of the system (reference state temperature and the atmospheric pressure are 4 °C and 101.32 kPa, respectively) for the SGDHS

Components	Exergy destruction rate (kW)	Utilized power (kW)	Heat transfer rate or installed power (kW)	$\dot{P}$ (kW)	$\dot{F}$ (kW)	Energy efficiency (%)	Exergy efficiency (%)
Heat exchanger	409.85	10,226.83	43,961.38	1402.17	1812.02	—	77
Well pump							
I	13.43	20.25	55	6.82	20.25	65–80	34
II	6.00	20.25	45	14.25	20.25	65–80	70
III	21.89	24.75	45	2.86	24.75	65–80	12
IV	0	—	—	—	—	65–80	0
Booster Pump: Salihli	11.37	55	675	43.63	55	65–80	79
Circulation pump: Salihli	12.56	112.5	537	99.94	112.5	65–80	91
Heat exchangers (VI)	409.85	10,226.83	43,961.38	1402.17	1812.02	—	—
Pumps (I–V)	65.25	241.69	1559.2	167.5	232.75	—	—
Overall system[a]	942.84	1569.67	45,520.58	1569.67	2044.75	55.6	59.8

[a]Based on the exergy (or energy) input to thermal water.

loss occurs to be 20.39%, specifically in the natural direct discharge. The second largest exergy destruction occurs within the heat exchanger with 17.42% of the total exergy input (i.e., corresponding to about 409.85 kW). This is followed by the total exergy destruction associated with the pumps amounting to some 65.26 kW, which accounts for 2.78% of the exergy input to the system.

Table 7
Energetic and exergetic data provided for one representative unit of the system (reference state temperature and the atmospheric pressure are 4 °C and 101.32 kPa, respectively) for the GGDHS

Components	Exergy destruction rate (kW)	Utilized power (kW)	Heat transfer rate or installed power (kW)	$\dot{P}$ (kW)	$\dot{F}$ (kW)	Energy efficiency (%)	Exergy efficiency (%)
Heat exchanger							
I	106.98	7148.09	23,260	987.25	1094.23	—	90
II	59.81	4293.54	13,956	597.45	657.26	—	91
III	21.04	1427.28	4652	197.45	218.49	—	90
Well pump							
IV	22.67	44	44	21.33	44	65–80	48
V	21.98	36	36	14.02	36	65–80	39
VI	20.32	36	36	15.68	36	65–80	44
VII	21.12	36	36	14.88	36	65–80	41
VIII	38.41	55	55	16.59	55	65–80	30
Circulation pump: Gonen	226.34	353	456	126.66	353	65–80	36
Pump of pressurized water tank: Gonen	35.95	36	36	0.05	36	65–80	—
Heat exchangers (I–III)	187.83	12,868.91	41,868	1782.15	1969.98	—	—
Pumps (IV–X)	386.78	596	699	209.21	596	—	—
Overall system[a]	1047.76	1991.36	42,567	1991.36	2565.98	44.5	63

[a]Based on the exergy (or energy) input to thermal water and water.

5.3. The performance evaluation results of the GGDHS

The total geothermal reinjection fluid (as the geofluid reinjected into the reinjection well) mass flow rate is 110 kg/s at an average temperature of 39 °C and the production well total mass flow rate is 110 kg/s. It shows that no pipeline losses or ignored levels in the EPC (geothermal loop) and ECC, but the pipe line losses of the system occur in the EDC is then calculated to be 2.3 kg/s [12].

This clearly indicates that in the GGDHS there is a significant amount of thermal water reinjected. The energy and exergy efficiencies of the GGDHS are determined to be 44.5% and 63%, respectively. The energy and exergy specifications of the system are illustrated in Tables 5 and 7. The thermal reinjection accounts for 55.39% of the total energy input, while the heat exchangers gain 44.5%, and the pipeline losses of the system cover its 0.11%. The actual thermal data for energy and exergy analysis and performance assessment purposes were taken from the GGDHS' technical staff.

Table 5 shows that 37% of the total exergy flow entering the system is lost, while the remaining 63% is utilized. The highest exergy destruction occurs from the thermal reinjection as 15.57% of the total exergy input. The second largest exergy loss is found to be 13.66% from the pumps. This is followed by the total exergy destruction associated with the heat exchangers and pipe line losses amounts to some 219.6 kW, which accounts for 7.76% of the total exergy input to the system.

5.4. Parametric studies

Reference temperatures and atmospheric pressure were assumed to be 4 °C and 101.32 kPa, respectively. Furthermore, energy and exergy efficiency values are correlated and illustrated in Table 8, with high correlation coefficients. As expected, the lower the reference state temperature, the significantly larger the energy and exergy losses in the system pipeline and heat exchangers. However, energy and exergy rates of pipeline losses of the system, heat exchangers, and useful exergy increase considerably. The reason for this rapid rise in energy and exergy rates is due to a decrease in the ambient temperature [5–13]. Based on these, we do curve-fitting to observe the trend of the energy and exergy efficiencies of the BGDHS, SGDHS, and GGDHS in Table 8. These correlations are capable of predicting the values of energy and exergy efficiencies of the Balcova, Salihli, and Gonen GDHSs for different environment temperatures.

Using Eqs. (13)–(16), the fuel depletion ratio, relative irreversibility, productivity lack and exergetic factors of GDHSs are determined and the values obtained are shown in Table 9.

6. Conclusions

We have presented energetic and exergetic aspects of GDHSs in general and have evaluated the performance of the three GDHSs, namely the BGDHS, SGDHS, and GGDHS in Turkey, along with their essential system components such as pumps and heat exchangers through a comprehensive energy and exergy analysis. Thermal, production and injection data taken during the operation of the system are utilized in the analysis. The exergy destructions in the overall GDHSs are briefly quantified and illustrated using an exergy and energy analysis.

We can extract some concluding remarks from this study as follows:

- The total energy input values range from 17.02 MW to 101.22 MW for the reference state temperature of 4 °C while the total exergy input values vary from 2.35 to 16.49 MW, respectively.
- The total energy and exergy efficiency values vary between 39.6% and 55.6%, and 45.7% and 63% at a reference temperature of 4 °C, respectively.
- While the SGDHS has a higher energy efficiency than the BGDHS and GGDHS, the GGDHS has highest exergy efficiency among these systems.
- In comparison with other local district heating systems (e.g. Balcova and Salihli GDHSs), the GGDHS has higher exergy values since its pipeline losses are lower than those of the Balcova and Salihli GDHSs.
- The energy recovery is crucial and should be implemented and with more effective reinjection wells and will result in less energy consumption in the BGDHS and SGDHS. It is also observed that automatic control of the GDHSs components and process in general will reduce the losses and human involvement and make the system more effective and efficient.
- Three empirical correlations based on the ambient temperature are developed to estimate the effective energy and exergy efficiencies.
- Reinjection of spent geothermal fluids is critical to good reservoir management, efficient resource utilization and reservoir conservation.

Table 8
Parametric studies on energetic and exergetic efficiencies of the GDHSs studied

Geothermal district heating systems	Energy efficiency correlation	Correlation coefficient (R^2)	Exergy correlation	Correlation coefficient (R^2)
BGDHS [9]	$\eta_{c1} = 2.10^{-5}T_a^3 - 0.0029T_a^2 + 0.3228T_a + 38.27$	0.99	$\varepsilon_{c2} = -6.10^{-5}T_a^3 + 0.0004T_a^2 - 0.1279T_a + 45.21$	0.99
SGDHS [9]	$\eta_{c3} = 0.0014T_a^3 - 0.0349T_a^2 + 0.7423T_a + 53.69$	0.99	$\varepsilon_{c4} = 0.0007T_a^3 - 0.0396T_a^2 - 0.1412T_a^2 + 0.4593T_a + 58.25$	0.97
GGDHS	$\eta_{c5} = 0.4002e^{0.0352T_a}$	0.97	$\varepsilon_{c6} = 0.6022e^{0.0154T_a}$	0.99

Table 9
Some thermodynamic parameters provided for one representative unit of the whole systems studied (reference state temperature and the atmospheric pressure are 4 °C and 101.32 kPa, respectively)

Component	Relative irreversibility χ (%)			Fuel depletion rate δ (%)			Productivity lack ξ (%)			Exergetic factor f (%)		
	BGDHS	SGDHS	GGDHS	BGDHS	SGDHS	GGDHS	BGDHS	SGDHS	GGDHS	BGDHS	SGDHS	GGDHS
Heat exchangers	85.09	86.27	32.69	12.32	20.04	7.32	15.84	26.11	9.43	93.73	88.62	76.77
Well pumps	10.91	8.7	21.65	1.76	2.02	4.85	2.1	2.62	6.25	2.99	3.19	8.07
Circulation pumps	0.79	2.64	39.4	0.13	0.61	8.82	0.15	0.80	11.37	2.21	5.50	13.76
Booster pumps	2.56	2.39	—	0.42	0.56	—	0.49	0.72	—	0.95	2.69	—
Pump of pressurized water tank	0.65	—	6.26	0.11	—	1.40	0.13	—	1.80	0.12	—	1.40
Overall system	100	100	100	14.74	23.23	22.39	18.71	30.25	28.85	100	100	100

- Significant energy can be lost to environment through losses (thermal and fluid losses), through poorly designed, constructed and maintained piping networks, through inefficient heat exchangers, poor pump selection, etc. as well as through heat utilization at end use equipment.
- Much more emphasis should be placed upon proper system design and project implementation issues, with use of the case studies only to illustrate various aspects.
- The results are expected to be beneficial to the researchers, government administration, and engineers working in the area of GDHSs.

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